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Spatial Correlation of Seismic Slip at the HDR-Soultz Geothermal Site: Qualitative Approach

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Abstract One major goal of monitoring seismicity accompanying hydraulic fracturing of a reservoir is to obtain information about the pattern, size, and orientation of fractures. The traditional method is to analyze the pattern of locations of the induced microearthquakes. To investigate whether additional information about the fracture pattern may be obtained from induced microearthquake datasets, we applied variogram analysis to investigate the spatial distribution of shear displacement at the source of microearthquakes. Variography is a method for analyzing spatial interdependence of a variable. The method was applied to a set of induced microearthquakes observed in the vicinity of the GPK1 injection well at Soultz-sou-Forêts Hot Dry Rock geothermal site (Alsace, France). Variograms obtained for 20 vertical slices (zones) along the wellbore were compared with the orientation of the fractures derived from a Formation Micro Imager, which is a resistivity log for measuring position and orientation of fractures in a borehole. We found that variograms exhibiting spatial dependency correlated well with zones where fractures belong to one dominant orientation set and variograms with no or low spatial dependency corresponded to zones with two or more fracture orientations/sets. We propose that this correlation results from the relation between the spatial variation of shear displacement, the physical properties of fractures, and their orientations.

Introduction

The hot dry rock geothermal energy (HDR) concept relies on the use of hydraulic fracturing to enhance rock mass permeability through the creation of fractures between injection and recovery wells drilled into nearly impermeable rock. Based on studies carried out at the Los Alamos National Laboratory (Los Alamos, New Mexico) and Camborne School of Mines (Reolruth, Cornwall, U.K.), it was suggested that the cause of permeability enhancement is due to shear failure induced along naturally existing joints by elevated pore fluid pressures (Fehler, 1989; Jupe, 1990). Several techniques exist to discern structural details within the zone of locations of the induced microseismic events (Fehler *et al.,* 1987; Jones and Stewart, 1997; Phillips *et al.,* 1997). These methods rely on the locations of the event hypocenters to define features in the event cloud. Another approach is the use of fault-plane solutions (Fehler, 1990), which provide information about both the structure and mechanism of shearing. Roff *et al.* (1996) used the ratio of *P*- to *S*-wave first-arrival amplitudes at a given station as an indicator of earthquake focal mechanism of clustered events. They analyzed the pattern of locations within the clusters and identified planes, which were considered to be fractures within the reservoir. Phillips *et al.* (1997) performed precise relative relocations of events in the Fenton Hill (northern New Mexico) reservoir by picking relative arrival times of events having similar waveforms. They found that events in many clusters fall along clear planes that can also be considered to be fractures within the reservoir.

The analysis of the displacement spectra of *P* and *S* waves radiated by induced seismic events gives information about seismic source parameters including seismic moment, magnitude, stress drop, shear displacement, and source radius (Brune 1970). Methods for calculation of the source parameters of seismic events induced by hydraulic fracturing and their physical interpretation are presented by Fehler and Phillips (1991) and Jupe (1990). While the source parameters themselves may be unreliable estimations of the actual source characteristics, their spatial variation within a hydraulically stimulated reservoir may provide useful information for understanding flow of fluids through the reservoir. In this article, we present a methodology for analyzing the spatial variations in computed shear displacement. We compare the parameters characterizing the spatial variation with measured fracture orientation and fracture density and propose a conceptual model linking seismic slip with physical properties of the reservoir. We test the method on a large data set of induced seismic events that occurred during stimulation of the HDR reservoir at Soultz-sous-Forêts, France.

Conceptual Model of Spatial Variability of Seismic Slip

The spatial variability concept has been used in many fields of earth sciences to identify relationships characterizing the spatial variability of observed data, which are then interpreted in terms of some controlling physical phenomena (Journel and Huijbregts, 1978; Hohn, 1988; Isaaks and Srivastava, 1989). The approach is a statistical one in which continuity or changes in parameters with position are investigated. Spatial variability analysis has never been used to investigate source parameters of earthquakes, although relations among source parameters and spatial position have been noted (Fehler and Phillips, 1991).

Our investigation of the spatial variability of seismic slip is undertaken using the variogram function $G(h)$ defined as

$$G(h) = \frac{1}{2n} \sum [D(x) - D(x + h)]^2, \tag{1}$$

where D is a value of the parameter measured at location x, h is separation distance between two measurements, and n is the number of all possible pairs of D that are separated by h (adopted from Journel and Huijbregts, 1978). For each dataset we analyze, we assume that the variogram is independent of orientation and location and is a function of offset h only, that is, it is isotropic, homogeneous, and stationary. Figure 1 shows two example variograms. Parameters describing a variogram are its range, nugget, and sill. The range is the distance beyond which the value of the variogram levels off. The range is a measure of the continuity of the variogram and is usually associated with the size and extension of structural features (Journel and Huijbregts, 1978). The nugget is the value of the variogram at zero offset. Physically, the nugget is a measure of the fine-scale variation in the parameter under study. Sill is the value of the variogram at large separation distance.

We use the variogram to investigate shear displacements along faults calculated from spectral analysis of earthquake waveforms. For simplicity, we consider shear slip to be the dominant mode of failure even if jacking or a combination of the two may be significant in some circumstances. We adopt the basic concept of fluid-induced seismic (FIS) kinematic shear-creep presented by Knoll (1992). We assume that roughness along a fracture plane and inhomogeneity in stresses cause a stimulated fracture to slip in a series of episodes rather than as a single event. As a consequence, a number of seismic events are triggered along one fracture plane. We postulate that seismic slip along accompanying events along a given fault varies smoothly with hypocentral position along the fault. In other words, the difference in shear displacement between two nearby events is small and the difference gradually increases as the separation of events increases until the difference stabilizes beyond some distance referred to in geostatistics as the correlation length. We also expect that seismic slip for fractures with similar orientation will exhibit the same spatial correlation since they (fractures in the set) were likely formed during the same tectonic/geological episode and thus have similar mechanical/physical properties such as fracture roughness. Figure 2A shows a set of commonly oriented fractures (only one dominant orientation set) along which seismic events (open circles) are triggered. For such a fracture set, an overall pattern of spatial variation would be reflected by an omnidirectional variogram function with low nugget effect (small variance in slip value for short separation distance between pairs of seismic events), a definite sill, and a clear correlation length (variogram range). Figure 1A shows an idealized variogram for a parameter exhibiting a clear spatial relationship such as would be expected for seismic slip along fractures having the same orientation.

A different situation will result when seismicity triggers in a portion of reservoir with more than one fracture orientation set (Fig. 2B). The existence of different orientation sets could be a result of distinct tectonic episodes forming distinct fracture sets, anisotropic rock stress distribution, elastic rebound, or lithological inhomogenities. Therefore we would anticipate that physical/mechanical properties of fractures of one set would differ from the properties of the other set. According to Barton *et al.* (1995), field evidence

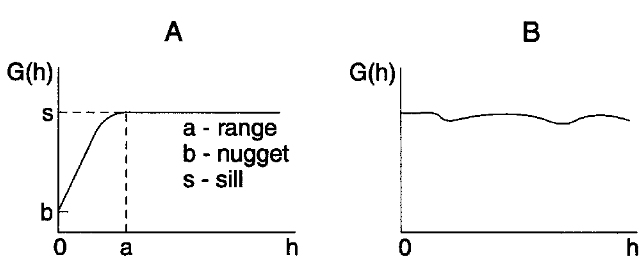

Figure 1. Sample variograms $G(h)$ as a function of separation distance h. (A) For a variable exhibiting spatial correlation with sill, s, range, a, and nugget, b. (B) For a variable manifesting no spatial correlation.

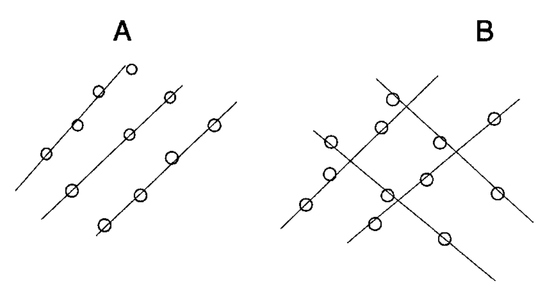

Figure 2. Schematic representation of locations of seismic events (open circles) triggered on preexisting fractures. (A) Fracture system has one dominant orientation. (B) Fracture system has two dominant orientations.

exists that genetically different fracture generations may have contrasting hydraulic properties, for example, as a function of the orientation relative to the present-day stress field or the nature of the materials filling the fractures. It is not unreasonable to postulate that estimates of shear displacement reflect to some degree those fracture parameters that influence its hydraulic features, for example, the aperture prior to shearing or distribution of infillings on fracture surface. Thus, for such a fracture configuration, we do not expect as clear a spatial correlation of seismic slip as for a single-orientation fracture population. In general, seismic slip estimated for fracture sets as depicted in Figure 2B will show some "random" behavior with distance because the events/locations from two different sets situated close to the fracture intersections and thus separated by a small distance will exhibit large differences in slip. Hence there is no smooth variation in slip with changing spatial separation. Consequently, the variogram will show either a weak spatial correlation or a random character of the shear displacement in space. Figure 1B depicts a possible variogram for slip along fractures in Figure 2B.

Our conceptual model proposes a relationship between spatial variability of slip and diversity of fracture orientation. When fractures of one orientation exist, slip will vary smoothly with position, and we anticipate that variograms will have a shape like the one in Figure 1A. When fractures of more than one orientation exist, slip does not vary smoothly with position, and we expect variograms that are different from the one in Figure 1A. If slip varies randomly with position, we expect variograms to appear similar to the one in Figure 1B. We will investigate this relationship by comparing variograms calculated in a zone of induced seismicity with borehole logs that provide information about fracture orientations. In the following sections we describe an approach to test our hypothesis using a dataset collected during an injection experiment at HDR-Soultz-sous-Forêts in Alsace, France.

Variogram Analysis of Induced Earthquake Shear Displacements Observed at the Soultz HDR Site

The data used for our analysis were collected at Soultz-sous-Forêts HDR site during a hydraulic injection conducted in September 1993. During the injection, a total of 25,300 m^3 of water was injected into wellbore GPK1. Water left the wellbore between depths of 2850 and 3400 m. Some aspects of the observed seismicity have been discussed by Phillips (2000). Seismic source parameters for 12,310 events were calculated by Robert Jones (personal comm., 1999), who followed Brune's (1970) approach. Shear displacement for each event was calculated using the equation from Aki and Richards (1980):

$$D = \frac{M_0}{\mu \pi R^2} \tag{2}$$

where D is shear displacement, M_0 is seismic moment, μ is compressibility modulus, and R is source radius.

Since the investigation of our conceptual model involves comparing the variogram calculated for seismic slip with fracture data in the well GPK1, the events located closest to the borehole were chosen for our analysis. We selected the events located within two orthogonal slices centered along the well GPK1 and striking north–south and west–east, respectively. Each slice was 100 m wide, 60 m thick, and extended from 2850 m to 3400 m in depth. Figure 3 displays the events within the slice along the west–east direction, which had 465 events. The north–south slice contained 428 events. Each slice was divided into ten 100-meter-long windows along the depth direction, and the variogram analysis was performed for each window. The analysis followed a moving/sliding window procedure with 50-m overlap, that is, the first analyzed window was 2850 m to 2950 m, the second window was 2900 m to 3000 m, the third one was 2950 m to 3050m, and so on. We thus computed a total of 10 variograms for each of two orthogonal slices. The results for the west–east slice are presented in Figure 4. Results for the north–south slice are similar to those for the west–east slice. By inspecting the shapes of the

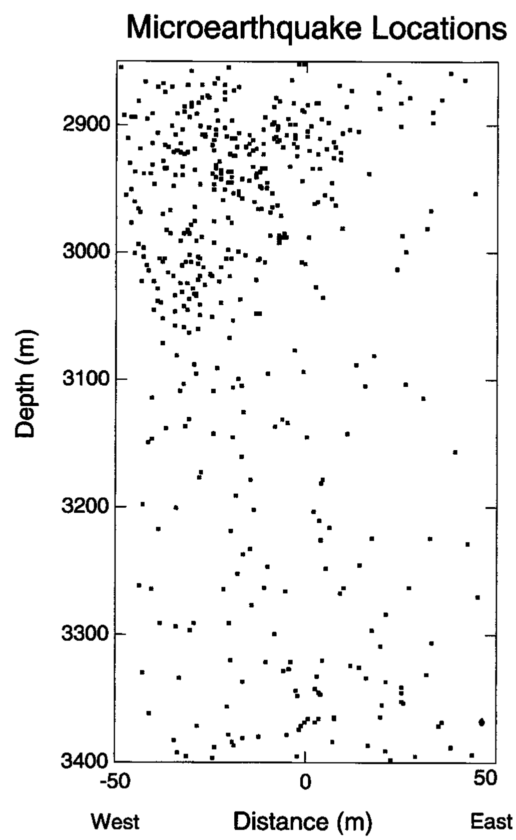

Figure 3. Location of seismic events, projected onto the west–east direction, that occurred during the injection experiment at the Soultz HDR site in September 1993. The thickness of the slice in the north–south direction is 60 m.

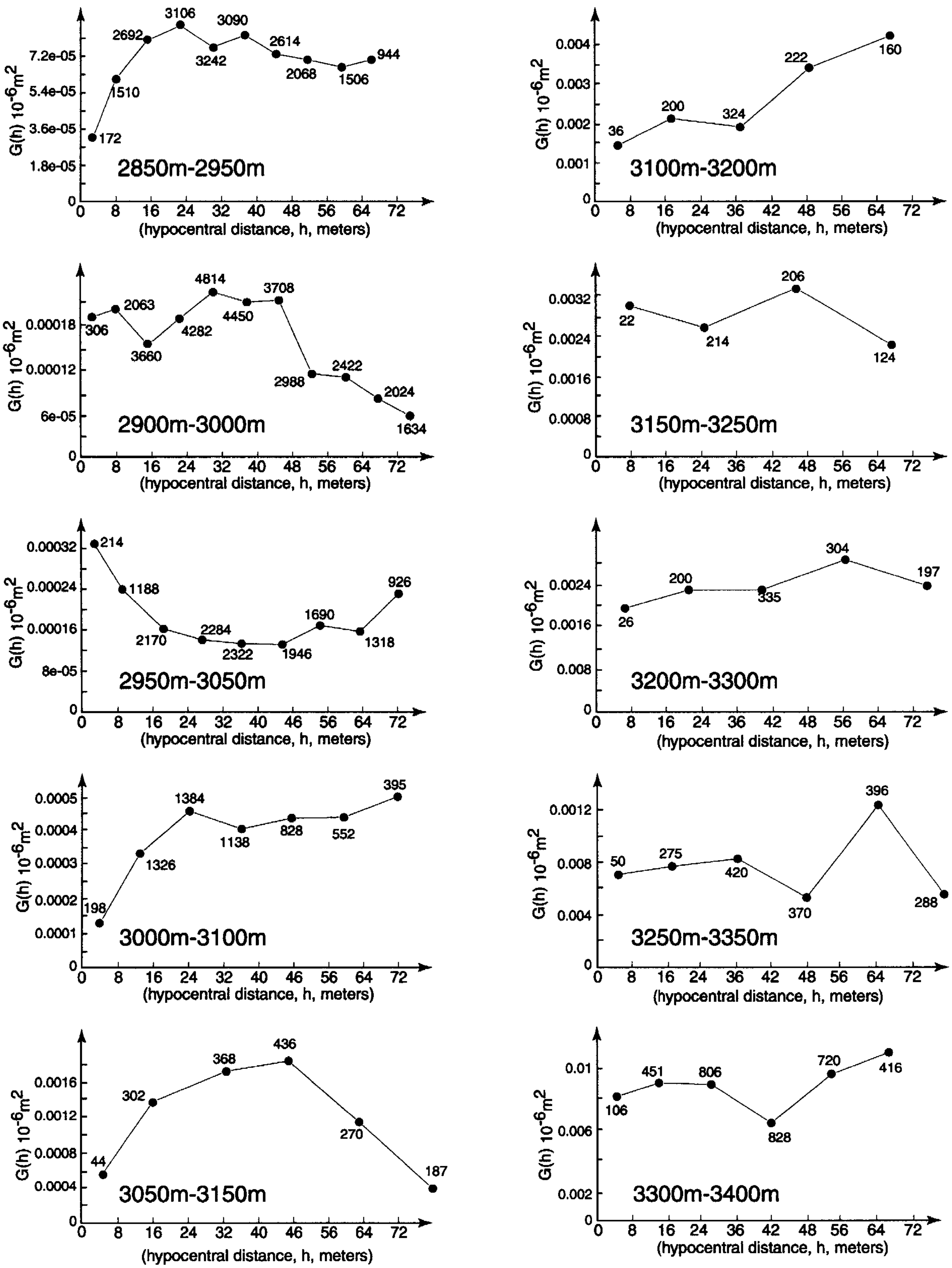

Figure 4. Variograms of shear displacement as a function of hypocentral separation distance for the west–east projection of seismic data. Depth intervals are indicated for each plot.

variograms we find that some have shapes similar to the one in Figure 1A and thus reflect a spatial correlation of slip (see depth intervals: 2850 m to 2950 m, 3000 m to 3100 m, and 3050 m to 3150 m). These variograms have low nugget value (relative to the sill value) and measurable range. (We focus only on variogram shape and range and do not investigate the absolute values of the variograms.) Many depth ranges have variograms similar to the one in Figure 1B, implying random spatial variations of slip (e.g., the depth interval 3150 m to 3250 m). Variograms for other depth ranges decrease with increasing separation distance (e.g., the interval 2900 m to 3000 m) or seem to trend toward infinite sill (e.g., the interval 3100 m to 3200 m).

Relationship between Spatial Pattern of Seismic Slip and Fracture Orientation at the Soultz HDR Site

We have found that within some intervals along the well GPK1, seismic slip exhibits clear spatial correlation, while other segments have no clear spatial pattern. Figure 5 presents a depth distribution of fracture dip trend (raw data) obtained from Formation Micro Imager (FMI) borehole logging in GPK1 (Genter *et al.,* 1995). We group together fractures in close proximity to each other that exhibit similar dip trend. The grouping was based on a visual examination and is not supported by any statistical measure of accuracy. However, the grouping indicates (see clusters 1a to 10) that fractures form distinct orientation groups/sets along the borehole. From Figure 5 it can be seen that within the depth interval from roughly 2850 m to 2950 m, there is one dominant dip trend ranging from 230 to 320°, which consists of fractures in clusters 1a and 1b. This is also a region where variograms of slip show spatial correlation (Fig. 4). In the depth interval 2950 m to 3050 m, there are two dominant fracture dip trends; cluster 2 with an average dip trend about 290°; and cluster 3 with an average of 100°. The variograms within this depth interval demonstrate a very poor or no spatial correlation (Fig. 4). Within the depth interval 3000 m to 3100 m, there is again one dominant fracture dip trend (cluster 4). For this sector the variogram function shows a clear spatial correlation. The depth sector between 3050 m and 3150 m is the last one where a single dip trend exists (cluster 4). Even though clusters 5 and 7 overlap into this sector, the fractures from cluster 4 dominate; this seems to be reflected in variogram shape that still manifests spatial dependency but with some signs of "distortion" (see Figure 4). The remaining well section, 3150 m to 3400 m, consists of two or three dip trend groups (clusters 5 to 10) and the variograms computed within the corresponding depth intervals do not show any clear signs of spatial correlation.

In contrast to dip trend, there is no clear correlation between fracture dip angle (Fig. 6) and shape of variograms for slip. Except the small cluster at about 3200 m depth, the dip angle varies between 50 and 88° with a tendency toward less steeply dipping fractures in the deeper section of GPK1. Comparing with fracture density reported by Genter *et al.* (1995), we find no correlation between slip variogram shape and fracture density in GPK1.

Uncertainties and Limitations of Variogram Calculations

There are several sources of uncertainty influencing calculated variograms, and there is no simple way to quantify errors. Thus we discuss the main sources of error that may influence the variogram shapes calculated in this study.

The variograms were computed within slices of dimensions 100 m by 100 m by 60 m. This choice of dimensions was a result of several considerations. First, it was important to see how the seismic slip varies close to the borehole in order to compare its spatial pattern with fracture data obtained from the fracture logging. Thus, the events located far from the borehole were of less importance. However, using too small a window in the variogram analysis may result in an insufficient number of data points and unreliable variogram estimation. In addition, small window sizes lead to edge effects, that is, the structure a variogram displays would depend more on the size of the window than the data within the window itself. The fact that the variogram ranges were found to be significantly less than 100 m gives us some confidence that the errors related to the window size did not influence the variogram calculation. The variograms are calculated using measurements at only a limited number of nonuniformly located points within each depth slice. To inves-

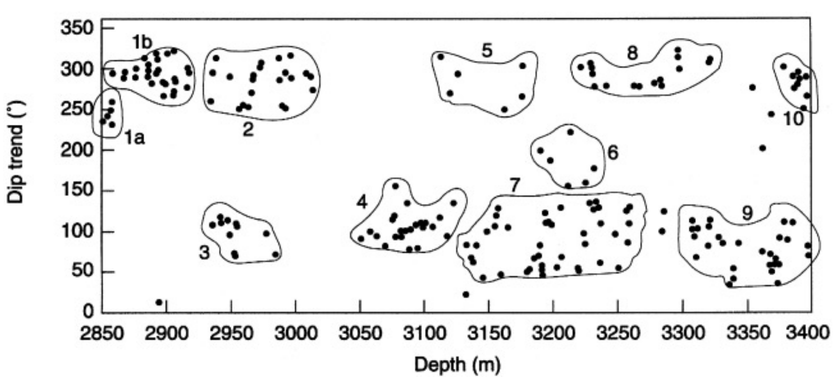

Figure 5. Distribution of fracture dip trend along GPK1 borehole. Data obtained from FMI logging by Genter *et al.* (1995). Clusters 1a to 10 indicate fractures having similar dip trend.

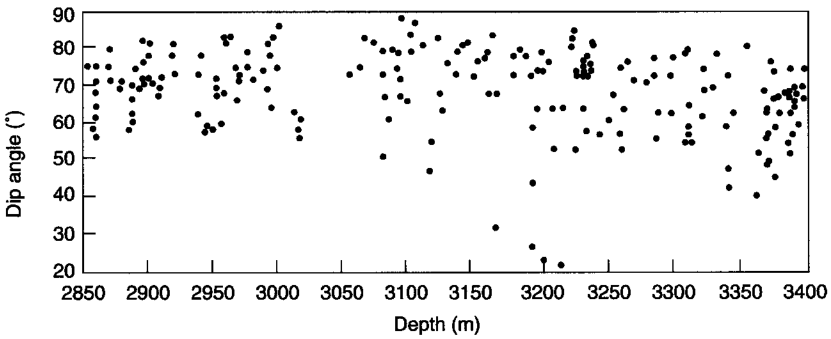

Figure 6. Distribution of fracture dip angle along GPK1 borehole. Data obtained from FMI logging by Genter *et al.* (1995).

tigate the effects of sampling with a small number of nonuniformly located points, we generated a test function that varied slowly in space. The test function was characterized by a Gaussian autocorrelation function (Sato and Fehler, 1998) having a correlation length of 20 m. This function was sampled on a uniform grid with a spacing of 1 m. We calculated the variogram of this test function using the uniformly sampled data and found that it had a shape similar to the one in Figure 1A and a range of close to 30 m. We then sampled this function at points equivalent to the locations where events were found to occur in our earthquake dataset. Variograms were calculated for each depth slice interval in a manner similar to the one used to construct Figure 4. We found that variogram shapes were not exactly the same as the one calculated from the entire test function dataset, but the shapes were similar to the one calculated for the test dataset. From this test, we conclude that sampling effects did not influence shapes of variograms calculated from our earthquake dataset.

Systematic errors in event locations probably introduce little structure into the shape of a variogram since variograms are functions only of separation between event locations and not the absolute locations. Random errors more than likely average out in the variogram process and thus have small effect on overall variogram shape. Such errors may vary with position within the reservoir. We have no way to reliably characterize systematic or random location errors or their influences on the variogram shape. As a simple test of the influences of locations on variogram shapes, we randomly assigned one of the source slips determined for a given microearthquake to another event within the same zone. We then calculated variograms for this randomized data. For each of the 20 windows, we found that the variograms determined using the randomized slips were nearly flat, indicating no correlation among randomized slip and event location. While this test does not place limits on the reliability of our reported variogram shapes, it does indicate that there is structure in the actual data that is not apparent in random data, even when microearthquake locations occur where they do in the actual dataset.

Conclusions

We found a correlation between the shape of variograms of shear displacement accompanying induced seismic events and fracture orientation of near-wellbore region. There is a clear difference in the variograms between zones with one dominant dip-trend fracture orientation and those with two or three dominating dip-trend orientations. We believe that this difference is a result of the correlation of spatial variability of seismic slip on the complexity of fracture network within a reservoir. While this correlation has been found to hold in the vicinity of a borehole, it may be reasonable to extend it to remote regions in a reservoir where it is desirable to make some inferences about fracture/joint geometry. The results obtained even if purely qualitatively can be helpful in verification of the conceptual model of seismic slip for the Soultz HDR site, however, more investigation is needed to examine the reliability of the method.

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